Overview 2003 of NASA Multi-D Stirling Convertor Code Development and DOE & NASA Stirling Regenerator R&D Efforts

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Abstract. This paper will report on (1) continuation through the 3rd year of a NASA grant for multi-dimensional Stirling CFD code development and validation, (2) continuation through the 3rd and final year of a Department of Energy, Golden Field Office (DOE), regenerator research effort and plans for NASA funding of a grant for continuation of the effort through two additional years, and (3) a new NASA Research Award for design, microfabrication and testing of a "Next Generation Stirling Engine Regenerator." Cleveland State University (CSU) is the lead organization for all three efforts, with the University of Minnesota (UMN) and Gedeon Associates as subcontractors. The Stirling Technology Co. and Sunpower, Inc. acted as unfunded consultants or participants through the 3rd years of both the NASA multi-D code development and DOE regenerator research efforts; they will both be subcontractors on the new regenerator microfabrication contract. Results of the NASA multi-D code development effort and the DOE regenerator research effort will be summarized. Plans for the NASA continuation of the DOE regenerator research effort include extension of the large-scale regenerator testing at UMN from a regenerator matrix of 90% porosity to one of 95%, measurement of thermal dispersion in the regenerator, investigation of the effect of various heat exchanger tube exit geometries on jetting into the matrix, continued regenerator CFD modeling at CSU, and heat transfer and pressure drop testing of random fiber regenerators with porosities as high as ~95% in the NASA oscillating-flow test rig on loan to Sunpower. Early results and planning for the new regenerator microfabrication contract will also be discussed.

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by

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Presented by
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Introduction
(How these efforts fit into the development of Stirling for space power)

- DOE, Lockheed-Martin, STC and NASA-GRC developing a high-efficiency Stirling Radioisotope Generator (SRG) for use on potential NASA space science missions
- Lockheed-Martin (LM) is under contract to DOE as the SRG System Integrator Contractor
- STC previously developed the Stirling convertor under contract to DOE, and is now continuing development as subcontractor to LM
- GRC is conducting supporting in-house technology and several advanced Stirling technology efforts
- The multi-dimensional (multi-D) code effort reported here is one of GRC's advanced Stirling technology efforts. The regenerator research grant and regenerator microfabrication NRA also fit in the category of advanced Stirling research.

Efforts Discussed in Paper

- NASA Grant for Multi-Dimensional Stirling Code Development and Evaluation
  - 4th year is now underway
  - CSU, UMN, Gedeon Associates with STC and Sunpower as unfunded participants
  - One Result: GRC has begun to work with a multi-dimensional model of STC's TDC

- First DOE, now NASA, Funded Efforts for Stirling Regenerator Research
  - Three year DOE contract just ended in August 2003
  - NASA Grant for 2 year continuation of effort began October 2003
  - CSU, UMN, Gedeon Associates, Sunpower with STC as unfunded participant

- NASA Research Award Contract for Design, Microfabrication, and Testing of a "Next Generation Stirling Engine Regenerator"
  - Began July 2003
  - Potential 3 year effort with each year after 1st optional, based on results
  - CSU, UMN, Gedeon Associates, STC and Sunpower

Multi-D Code Development and Validation Decisions & Procedure

- Commercial CFD-ACE code (CFD Research Corp.) chosen for code development

- Attractive CFD-ACE features: 2-D & 3-D capability; can model reciprocating moving boundaries; has many turbulence models and large eddy simulation (LES) capability; macroscopic porous media module; parallelized version for use with multiple processors; good pre- and post-processors

- In general, available engines haven't permitted detailed, accurate, internal measurements for code validation (speed too high, flow channels too small, oscillating flow/press./temp., etc.)

- Therefore, are concentrating on use of "simpler" test rigs that incorporate Stirling-like processes:
  - Published geometry and data from MIT gas spring and "two-space" test rigs
  - UMN "90 degree turn" test rig – testing complete
  - UMN regenerator test rig (from DOE & NASA regenerator research efforts)
  - CSU Stirling laboratory research engine (SLRE)
  - UMN "180 degree turn" or "expansion head" test rig –work just getting underway

- CSU has also developed a 2-D model of a complete CSUmod Stirling engine & GRC has converted it to model STC's TDC

2-D CFD-ACE Model of "Space Power Type" Stirling Convertor

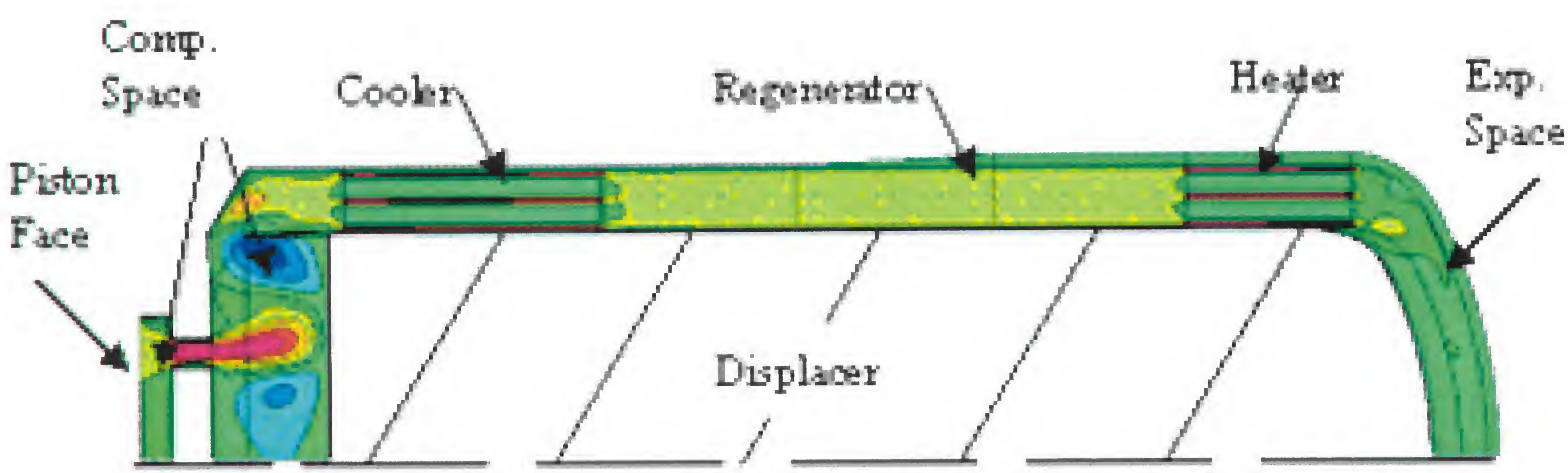


FIGURE 1. 2-D Stirling Convertor Schematic with Velocity Contours.

Update on 90° Turn Model Validation Experiments-1

(UMN Test Facility)

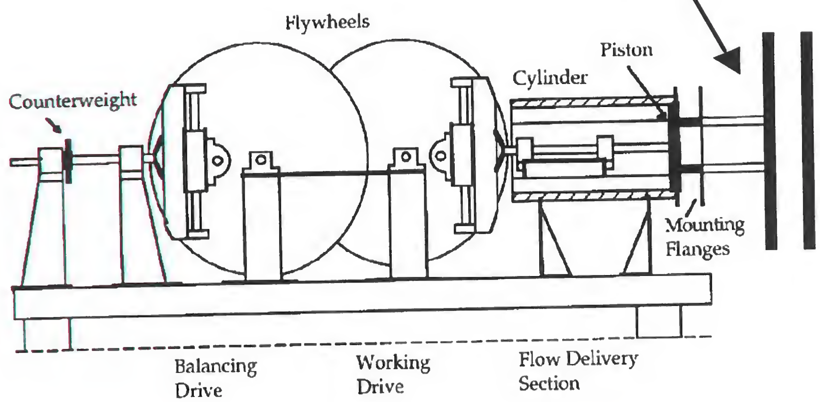
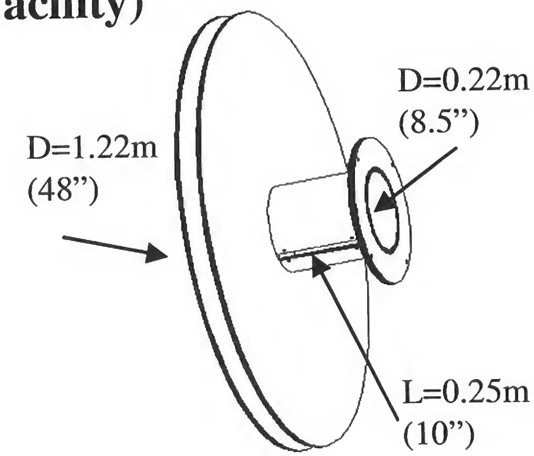


FIGURE 2. UMN Scotch Yoke Drive Facility.



IGURE 3. Test Section.

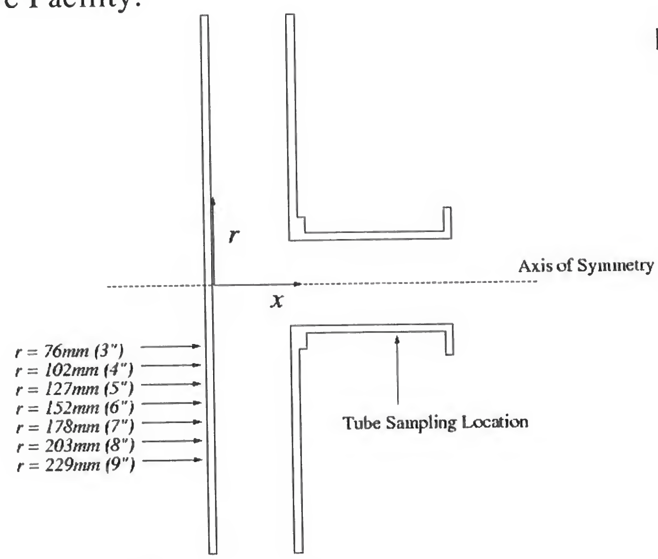


FIGURE 4. Sampling Locations and Coordinate Conventions.

Update on 90° Turn Model Validation Experiments-2
(UMN Test Results – Adolfson, Simon, et. al., 2003)

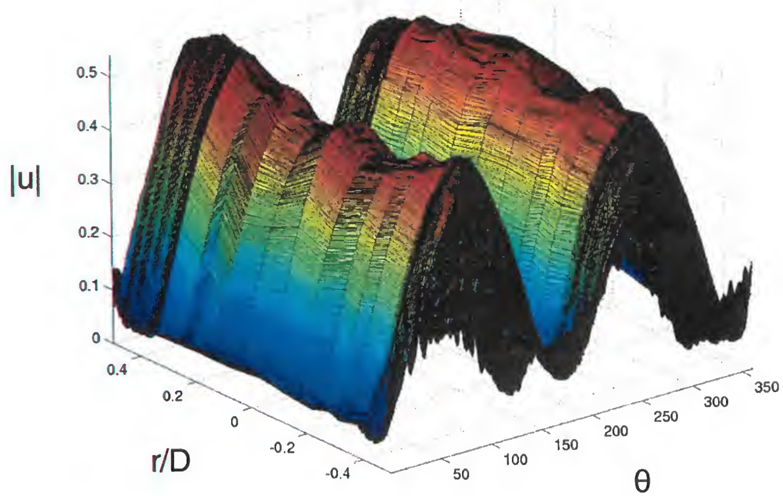


FIGURE 5. Velocity Profile in the Tube for Case II.a.

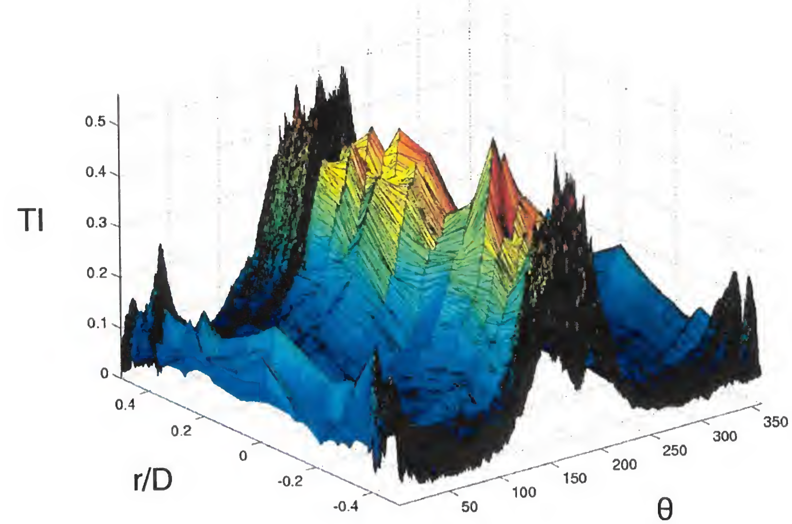


FIGURE 6. Turbulence Intensity Profile in Tube for Case II.a.

Case IIa: 30 RPM, Re = 7600, Va = 2300, Disk Spacing = 127mm (5")

0 º < θ < 180º Intake

180º < θ < 360 º Exhaust

Raw data averaged over 100 cycles

Hot wire unable to resolve flow direction

Update on 90° Turn Model Validation Experiments-3

Comparison of CSU CFD Calcs. & UMN Flow Viz. Experiments for <u>Unidirectional Flow</u>

(Ibrahim, Zhang, et. al., 2003a)

Laminar CFD Calcs. | **K-ω Turbulence Model** | **UMN Flow Visualization Exp.**

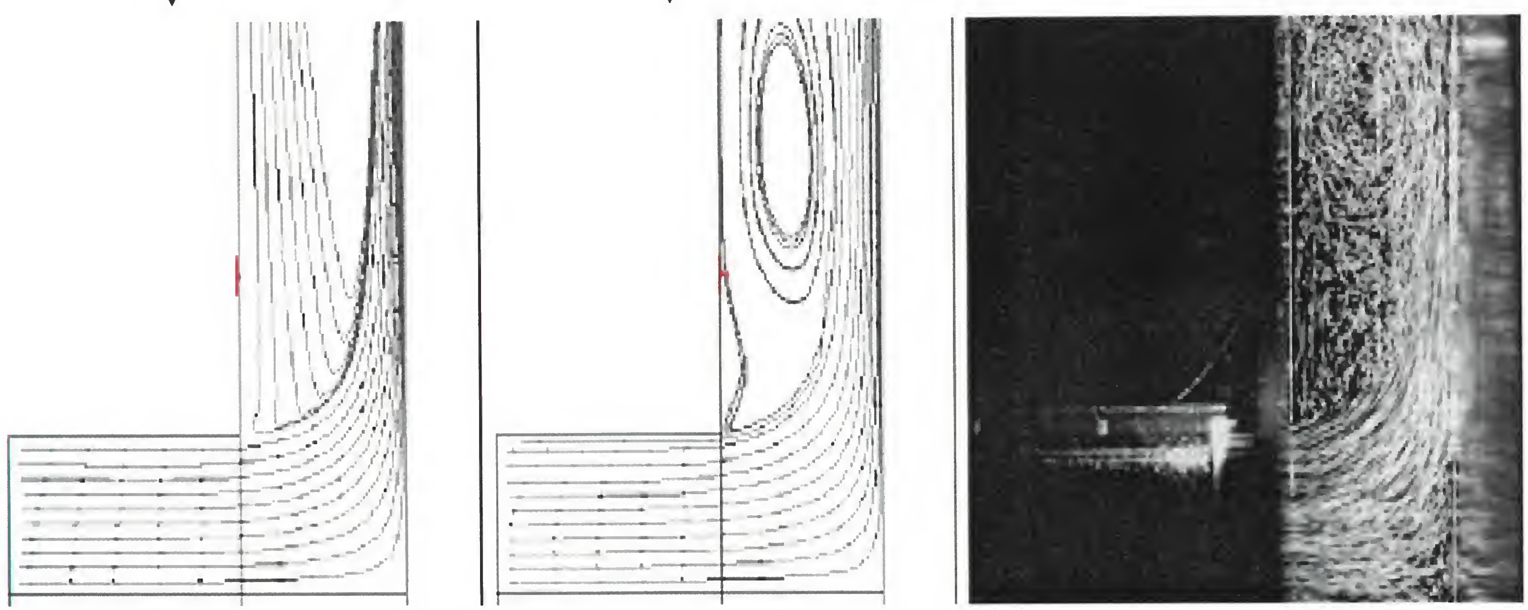


FIGURE 7. Comparison Between CFD (Streamlines and Velocity Vectors) and UMN Experiments (Flow Visualization), Disk Spacing -0.127 m, Maximum Reynols number=7600.

Update on 90° Turn Model Validation Experiments-4

Comparison of CFD Velocity Calcs. & Velocity Measurements for Unidirectional Flow (Ibrahim, Zhang, et. al., 2003a)

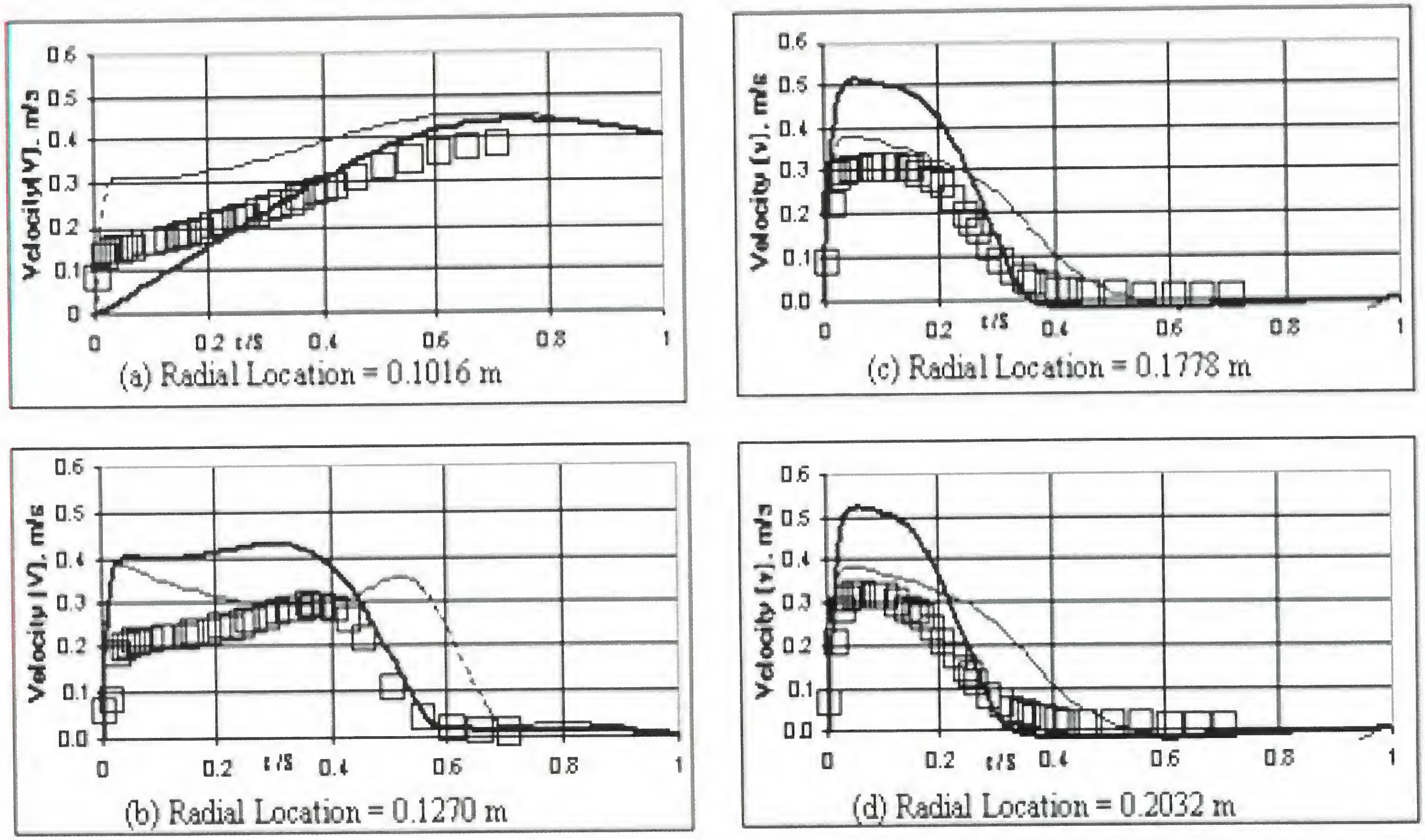


FIGURE 8. Comparison Between Experimental Velocity Data (UMN), Symbols, and CFD Results, Unidirectional Flow, Laminar, Solid Lines & K-ω, Dotted Lines, Turbulent Flow Models at Different Radial Locations: S=127mm and ReD =7600.

First DOE, now NASA, Regenerator Research Effort

- 3-year DOE contract to do fundamental regenerator research to achieve improvements in regenerator and Stirling convertor performance ended Aug. 2003. Aimed primarily at solar dish-Stirling systems

- A major part of this effort was testing at UMN in a large-scale low-frequency piston/cylinder-cooler-regenerator-heater test module; same driving device as for NASA grant test sections was used

- New NASA Regenerator Research Grant will move from 90% to 95% regenerator porosity, look at effect of various cooler end geometries, and will also fund testing of various regenerator matrices in the oscillating-flow test rig at Sunpower.

DOE Regenerator Research Test Section at UMN (Same Flow Driver as for 90º Turn Test Section)

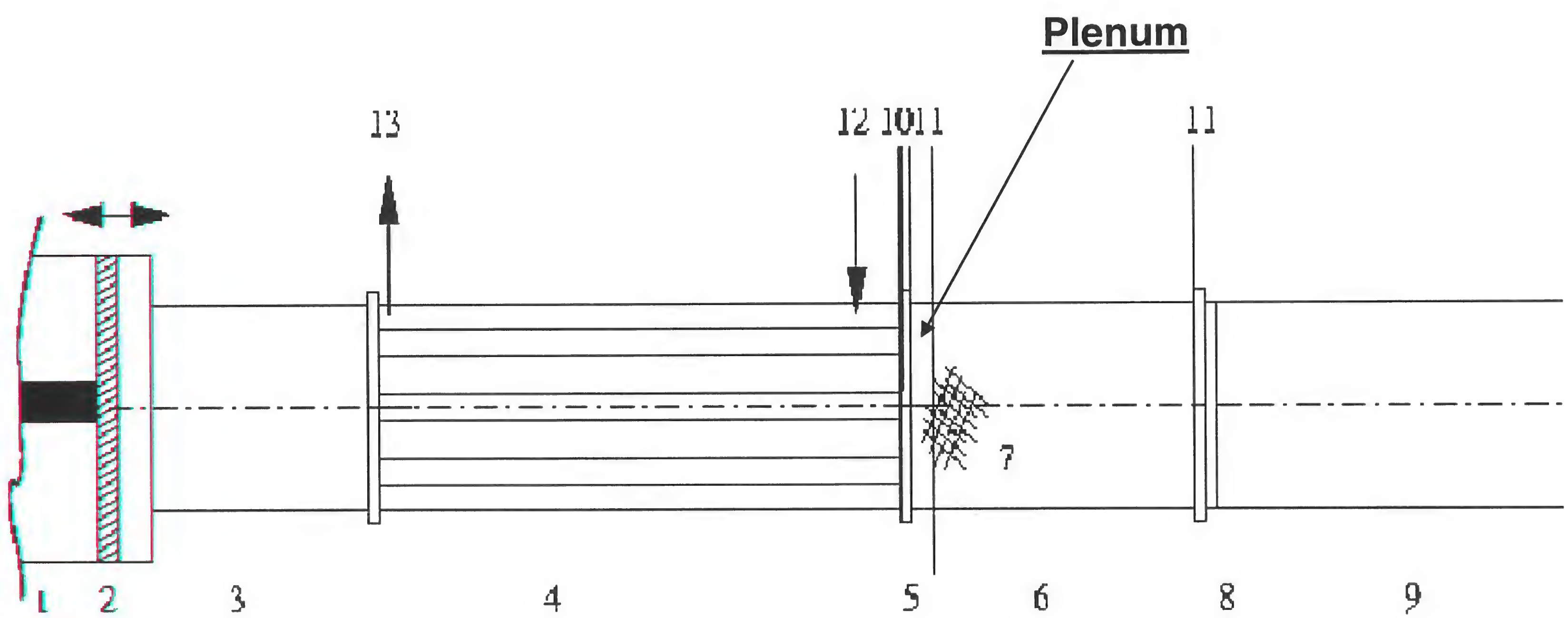


FIGURE 9. The Schematic of the UMN Experimental Facility and the Test Section.
1----oscillatory flow generator, 2----piston, 3----flow distributor, 4----cooler, 5----plenum, 6----regenerator, 7----screen matrix, 8----electrical hating coil, 9----isolation duct, 10----hot-wire, 11----thermocouple, 12----cooling water in, 13----cooling water out

Frequency = 0.4 Hz (24 RPM), Stroke = 356 mm, Piston Diameter = 356 mm
Regen. Porosity = 90%, Dimensionless Parameters Similar to an STC Engine

Regenerator Research Test Section:
Velocity Measurements in Plenum Between Cooler Tubes & Screens
(Niu, Simon, et. al., 2003c)

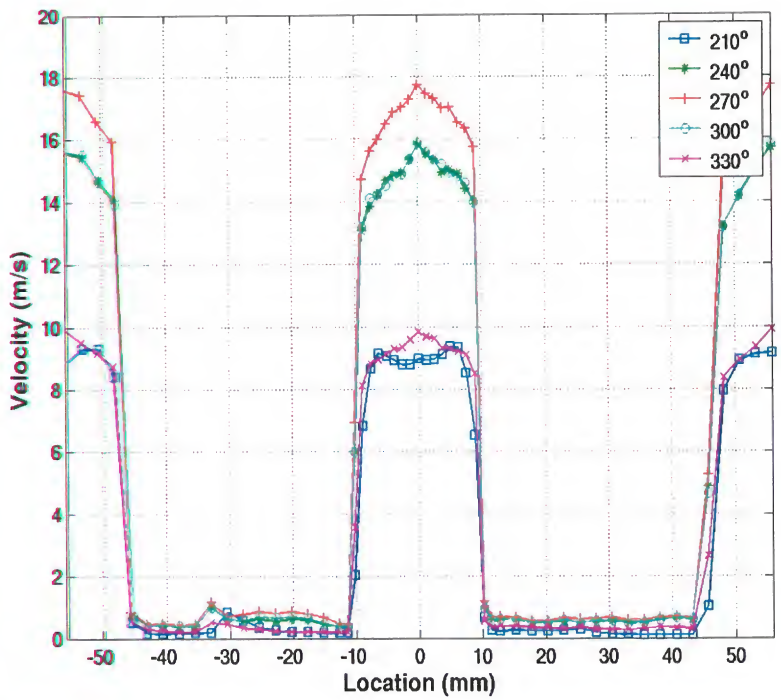


FIGURE 10. Velocity Profiles during the Blowing Half Cycle with the Plenum for Case I (1.33δ).

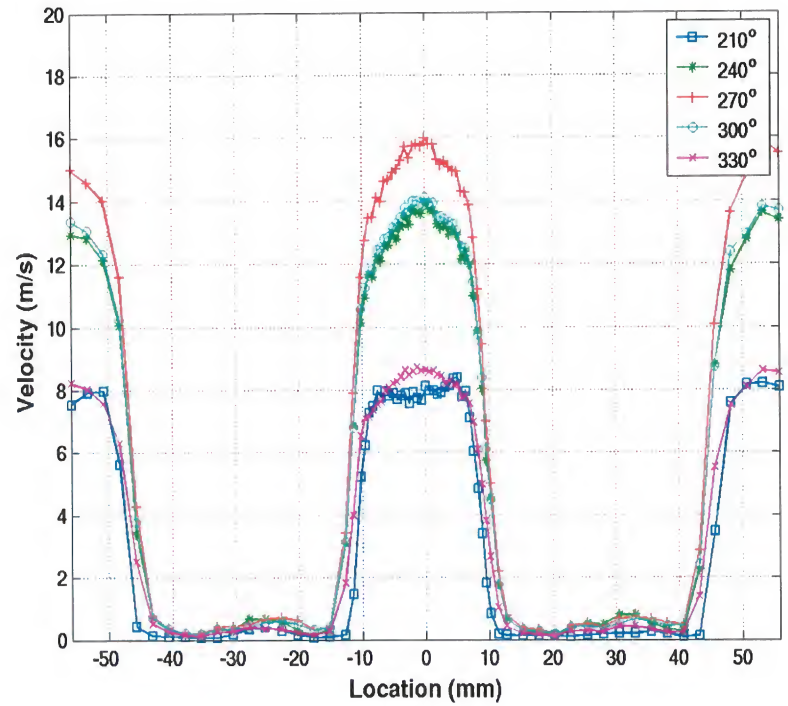


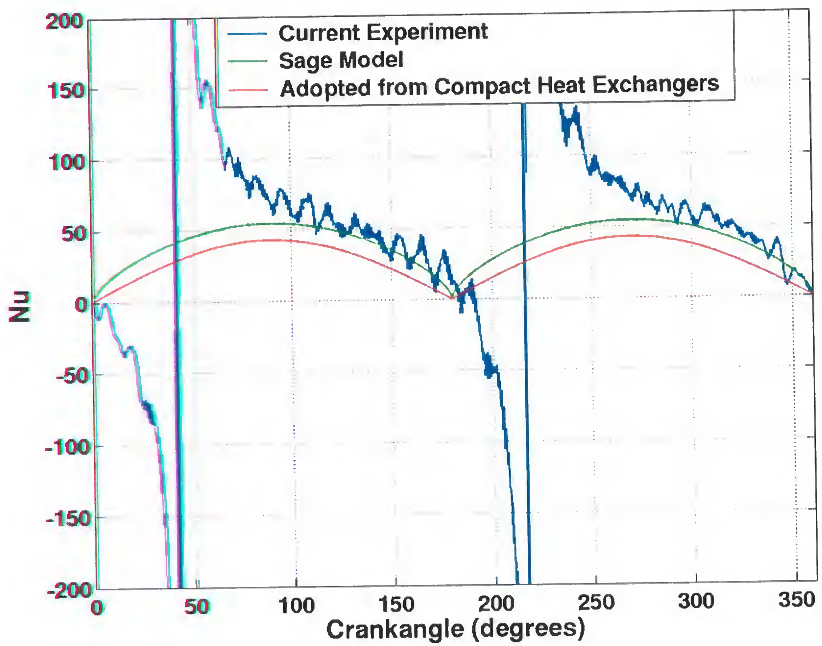
FIGURE 11. Velocity Profiles during the Blowing Half Cycle with the Plenum for Case III (4.33δ).

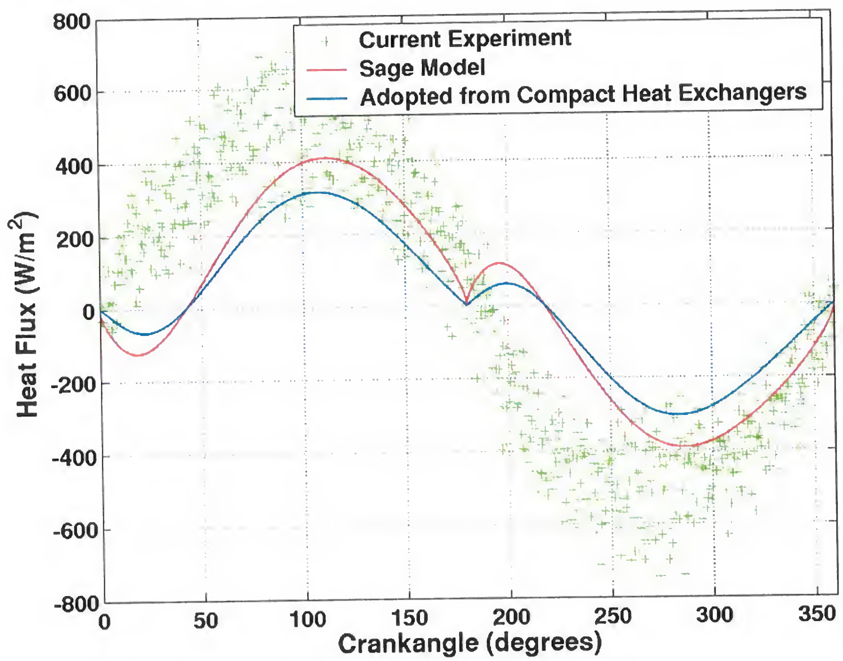
Nominal Plenum Width, δ = 4.76 mm
Case I Plenum Width = 1.33 δ & Case II Plenum Width = 4.33 δ

Conclusions of Cooler/Regenerator "Flow-Jetting" Tests

- Comparison of figures shows maximum velocity decreases with larger plenum from 17.8 to 16.0 m/s & also jet width increases slightly (more distance to spread)
- Niu (2003c) reports temperature measurements within plenum & matrix show jets spreading at wider angle as they enter the regenerator matrix—eventually merge
- Fraction of matrix not participating in heat transfer calculated for each case & was <u>weakly</u> dependent on plenum width (for 90% porosity matrix)
- The effect of thermal dispersion was also investigated, indirectly, by comparing jet spreading in matrix to spreading of free turbulent circular jet
- Estimated eddy diffusivity in a real engine due to dispersion would be 40-90 times the molecular diffusivity
- This implies the axial conductivity loss through the gas would be 40-90 times that due to the molecular conductivity
- Thermal dispersion & enhanced conductivity loss is due to "turbulent like" eddies formed as gas flows over and around the matrix wires

Regenerator Research Test Section: Heat Flux and Nusselt Numbers Resulting from Matrix & Gas Temperature Measurements





- Test results match quasi-steady Sage and Kays & London correlations during deceleration portion of cycle from 90º to 180º and from 270º to 360º

- During acceleration portion of cycle test results are not quasi-steady—but it was later determined they may not match engine conditions during acceleration

- Ibrahim (2003b) reports CSU CFD results agree qualitatively with UMN test results

NASA 2 Year Regenerator Research Grant: Follow-on Effort to 3 Year DOE Regenerator Research Contract

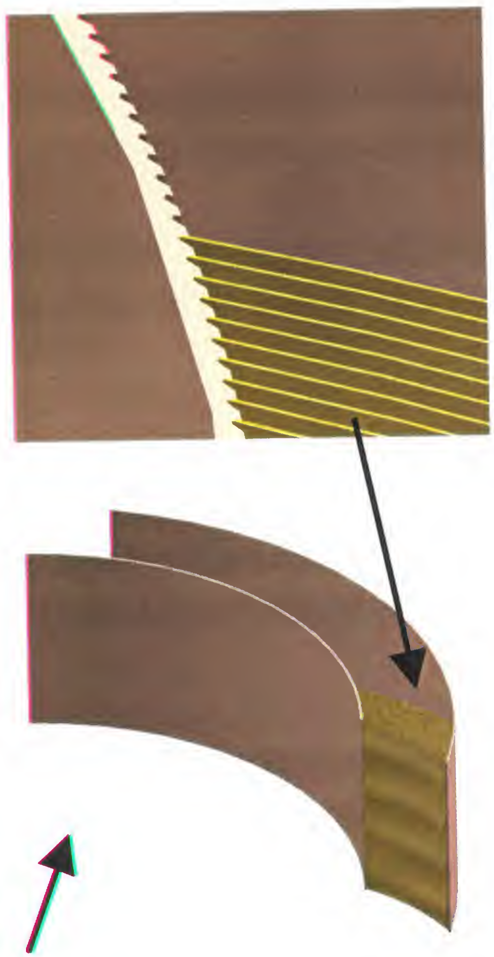
- Upgrade Sunpower oscillating-flow test rig data acquisition system & test about 15 random fiber regenerator samples with porosities as high as 95%

- Possibly—also test some more unusual regenerator samples such as "flattened & oriented" random fibers and etched foil

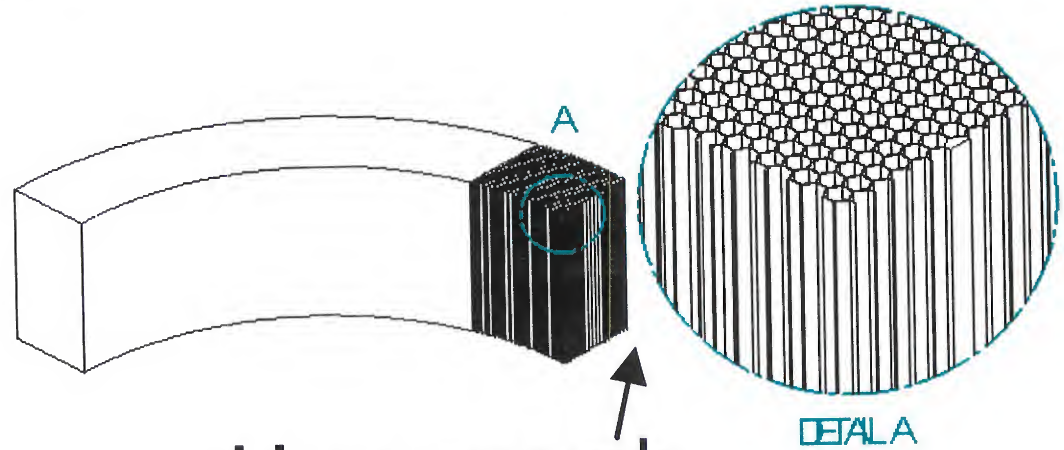
- At UMN:
  - Directly measure thermal dispersion in regenerator matrix
  - Extend large-scale regenerator testing from 90% to 95% porosity
  - Study effect of various cooler-tube exit geometries on jetting into matrix
  - Extend large scale measurements to some type of "random fiber" matrix

- At CSU:
  - Do CFD modeling to compare with UMN high porosity, random fiber and cooler-tube exit geometry testing
  - Do CFD study of effect of foil gap variations on foil regenerator perf. & compare with already complete Sage study of such variations
  - Develop porous media model with separate gas and matrix energy equations—to replace current CFD-ACE porous media module

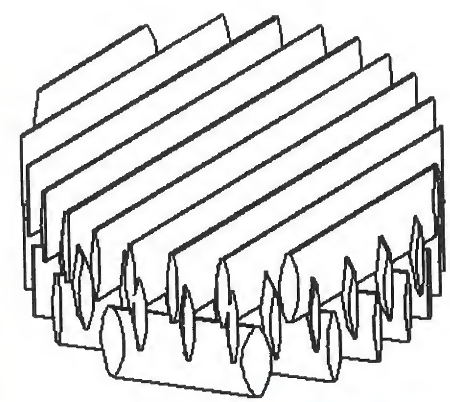
Regenerator Microfabrication Contract
Some Regenerator Microfabrication Concepts



Involute Foil



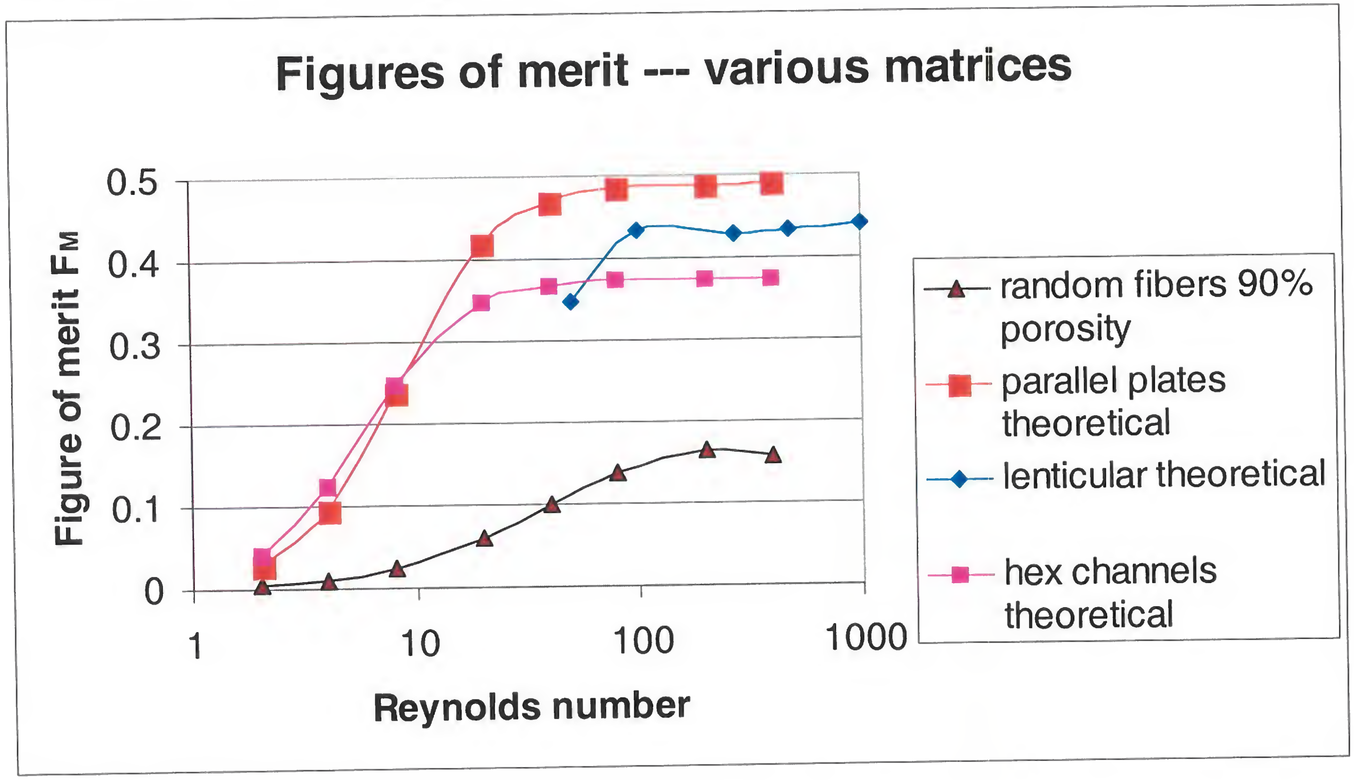
Honeycomb



Lenticular

Regenerator Microfabrication Contract
David Gedeon's Results

Potential 9% power increase for a micro-fabricated regenerator in a 100W-sized space-power engine



$$F_M = \frac{1}{f\left(\frac{R_e P_r}{4N_u} + \frac{N_k}{R_e P_r}\right)}$$

Where f is friction factor, N_u is Nusselt number and N_k is a "conductivity ratio" defined as the effective axial conductivity divided by the conductivity of helium

Regenerator Microfabrication Contract
1 Year Certain with Options for 2 more years

- 1st Year Includes:
  - Select regenerator matrix design, vendor and microfabrication technique
  - Develop large-scale-mock-up (LSMU) of design for testing at UMN
  - Modify & qualify UMN rig to accept LSMU & develop LSMU test plan
  - Develop CFD model of LSMU (at CSU)
  - Estimate engine performance improvement realizable with new matrix

- 2nd Year Includes:
  - Test LSMU & continue CFD modeling of LSMU
  - Fabricate proof-of-concept regenerator with actual-size features
  - Ascertain that features fall within desired specifications
  - Investigate how microfab. technique can be extended to an integrated heater / regenerator / cooler

- 3rd Year Includes:
  - Fabricate regenerator with actual size features for testing in the Sunpower oscillating-flow test rig & do the testing
  - Fabricate regenerator of appropriate size for testing in the chosen engine & do the engine testing
  - Design an integrated heater / regenerator / cooler
  - Continue LSMU testing & CFD modeling

Concluding Remarks

- Results of several Advanced Stirling Technology efforts summarized
- Goals are improvements in Stirling convertor performance via—
  - Development & validation of multi-D Stirling CFD models
  - Experimental & computational research to investigate regenerator fluid-flow and heat-transfer phenomena
  - Development of a new, improved regenerator via microfabrication
- Progress and problems associated with these Advanced Stirling Technology efforts are reported in this paper, and more fully in the papers referenced